PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
G01S 13/06, 13/18, 13/42, 13/72

A1

(11) International Publication Number: WO 97/22889

(43) International Publication Date: 26 June 1997 (26.06.97)

(21) International Application Number: PCT/AU96/00817

(22) International Filing Date: 19 December 1996 (19.12.96)

(30) Priority Data:
PN 7226 19 December 1995 (19.12.95) AU

(71) Applicant *(for all designated States except US)*: COMMONWEALTH OF AUSTRALIA [AU/AU]; Departement of Defence, Defence Materiel Division, Anzac Park Offices, Anzac Park, Canberra, ACT 2600 (AU).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: PULFORD, Graham, William [AU/AU]; 28 Sunhill Road, Glen Iris, VIC 3146 (AU). JARROTT, Robert, Keith [AU/AU]; 28 Bramley Road, Ringwood North, VIC 3134 (AU). EVANS, Robin, John [AU/AU]; 5 Bayview Lane, Aspendale, VIC 3195 (AU).

(74) Agents: WEBBER, David, Brian et al.; Davies Collison Cave, 1 Little Collins Street, Melbourne, VIC 3000 (AU).

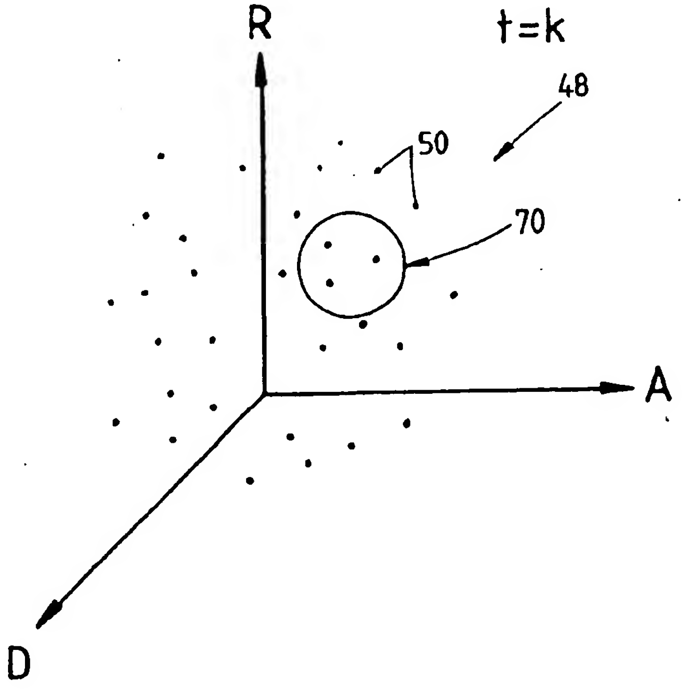
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, ARIPO patent (KE, LS, MW, SD, SZ, UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.

(54) Title: A TRACKING METHOD FOR A RADAR SYSTEM

(57) Abstract

A tracking method for a signal echo system, including generating a plurality of gates for respective propagation modes on the basis of a target state prediction for a dwell time, and generating a target state estimate for the dwell time on the basis of target measurement points which fall within the gates.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AM	Armenia
AT	Austria
AU	Australia
BB	Barbados
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BJ	Benin
BR	Brazil
BY	Belarus
CA	Canada
CF	Central African Republic
CG	Congo
CH	Switzerland
CI	Côte d'Ivoire
CM	Cameroon
CN	China
CS	Czechoslovakia
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GE	Georgia
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IT	Italy
JP	Japan
KE	Kenya
KG	Kyrgystan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
KZ	Kazakhstan
LI	Liechtenstein
LK	Sri Lanka
LR	Liberia
LT	Lithuania
LU	Luxembourg
LV	Latvia
MC	Monaco
MD	Republic of Moldova
MG	Madagascar
ML	Mali
MN	Mongolia
MR	Mauritania
MW	Malawi
MX	Mexico
NE	Niger
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation
SD	Sudan
SE	Sweden
SG	Singapore
SI	Slovenia
SK	Slovakia
SN	Senegal
SZ	Swaziland
TD	Chad
TG	Togo
TJ	Tajikistan
TT	Trinidad and Tobago
UA	Ukraine
UG	Uganda
US	United States of America
UZ	Uzbekistan
VN	Viet Nam

A TRACKING METHOD FOR A RADAR SYSTEM

The present invention relates to a tracking method for a radar system, such as a phased array radar system or a bistatic radar system. Although the following discusses use for radar systems, the invention could also be applied to other signal echo systems, such as sonar systems.

Radar signals returned from a target allow information to be determined concerning the slant range, azimuth and speed of a target relative to the receiving system of the radar system. The receiving system however normally receives a number of signals returned from the target which have different propagation paths or modes. Noise received by and induced in the receiving system can also be mistaken for a return signal from the target and needs to be taken into account. Tracking methods have been employed which track a target on the basis of signals relating to one propagation mode. Yet selecting one propagation mode neglects information relating to other modes which can be used to enhance the accuracy and sensitivity of the tracking method.

In accordance with the present invention there is provided a tracking method for a signal echo system, including:

generating a plurality of gates for respective propagation modes on the basis of a target state prediction for a dwell time; and

generating a target state estimate for said dwell time on the basis of target measurement points which fall within said gates.

The present invention provides a tracking method for a signal echo system, including:

obtaining target measurement points for a dwell time;

initiating tracking by obtaining an initial target state estimate from at least one of said points;

determining a target state prediction for a subsequent dwell time on the basis of said target state estimate;

generating a plurality of gates for respective propagation modes on the basis of the target state prediction; and

generating a target state estimate for said subsequent dwell time on the basis of target measurement points for said subsequent dwell time which are within said gates.

The target state estimate may be generated by applying association hypotheses to said measurement points in said gates and association probabilities to said hypotheses, obtaining conditional state estimates from the measurement points for each hypothesis and summing said conditional state estimates multiplied by said probabilities.

The tracking initiating step can advantageously be performed for a plurality of propagation modes to initiate a plurality of tracking filters by generating a plurality of said target state estimates for said subsequent dwell time.

The present invention further provides a tracking method for a signal echo system, including extending a target state vector to include additional parameters associated with a plurality of propagation modes, and accounting for measurement uncertainty associated with propagation path characteristics for said modes when updating target state estimates.

A preferred embodiment of the present invention is hereinafter described, by way of example only, with reference to the accompanying drawings, wherein:

Figure 1 is a schematic diagram of an over the horizon radar (OTHR) system;

Figure 2 is a diagram of a measurement frame of reference;

Figure 3 is a diagram of possible propagation modes;

Figure 4 is a graph of target tracks;

Figure 5 is a diagram of measurement geometry of the system; and

Figure 6 is a diagram of multiple gates for target state estimation.

Bistatic radar systems employ separate transmitter and receiver sites, and include

Over The Horizon Radar (OTHR) systems which direct transmission signals above the horizon for refraction by the ionosphere, known as skywave systems. OTHR systems also include surface wave radar systems which propagate radar waves along the surface of saltwater, and rely on the receiving system being able to detect objects by the radar signals reflected therefrom.

An OTHR system 2, as shown in Figure 1, includes a receiving system 4 and a transmitting system 6. The transmitting system 6 comprises an in-line array 7 of transmitting antennas located at the transmitter site and a control system 10 for feeding electrical signals to the antennas. The receiving system 4 comprises an in-line array 12 of receiving antennas and a control system 16 for processing the signals received by the antennas, which are located at the receiver site. OTHR systems include the Jindalee Facility in Alice Springs (JFAS) and the U.S. Navy's ROTHR system.

The broad transmitting beam of the radar is directed towards areas of the ionosphere from which refracted signals are redirected to monitor a target 3. The beam is effectively directed to a region or area in which a target is located. A number of targets may be located in one region and the receiver control system 16 is able to divide the energy returned from the illuminated region into a dozen smaller beams which can then each be divided into a plurality of range cells that are characterised by a respective distance from the receiving system 4. This allows the receiving system 4 to track a number of targets which are located in the illuminated region. The receive beams can also be divided into a plurality of velocity cells characterised by an object's velocity relative to the receiving system 4. This allows targets to be separated on the basis of their velocity if they cannot be separated on the basis of their distance from the receiving system 4. The transmitting and receiving beams can be moved or swept in synchronism, through a number of beam steer positions, with the time being spent at any given position being referred to as the dwell time. Measurements obtained from the radar signals or echoes received during each dwell time are referred to as dwells.

The control software of the control system 16 is able to obtain four parameters pertaining to a target from each dwell, and these are the propagation path length or slant range (R), azimuth (A), Doppler frequency shift or radial speed (D) and signal strength based on a signal to noise ratio (SNR) measurement. These are referred to as the RAD or radar coordinates. The set of measurements from a dwell also includes clutter and detections from other targets.

The dwells can be graphically represented by plotting them as candidate detection points on a three dimensional axis, as shown in Figure 2, for dwell $t = k$, where one axis represents R, the other A and the third the D values. For any dwell time $t = k$ of the order of 100 or 1000 candidate detection points 50 may be determined by the receiving system 4. Some of the points 50 may correspond to a target and others may simply relate to clutter echoes or noise intrinsic in the transmitting system 6 or receiving system 4. Clutter echoes arise from backscatter from the ground or objects which are not of interest, such as meteors. The OTHR system 2 is also subject to multipath propagation in that there is more than one single path for echoes returned from a target due to a number of different ionospheric layers 54 at different heights 53 which refract echoes down to the receiving system 4, as shown in Figure 3. There may be up to four different reflecting layers F_0, F_1, F_2 and F_3 resulting in several echoes returned from a target, corresponding to reflections from combinations of these layers. Propagation modes are described by the layers from which the signal is refracted. For example, F_0-F_1 is the propagation mode for a transmit path via layer F_0 and a receive path via layer F_1, where T represents the target 3, as shown in Figure 3. Whilst the propagation path for a candidate detection point 50 is not known, the height of the different layers can be determined using commercial ionospheric sounders which provides some information concerning the relationship between points of different propagation modes for the same target. Knowing the heights and properties of each layer gives an indication as to expected RAD measurements of different propagation modes.

The state of the target, at a given dwell k, can be represented by

$$x(k) = \begin{pmatrix} r(k) \\ \dot{r}(k) \\ a(k) \\ \dot{a}(k) \end{pmatrix} \tag{1}$$

where r is the range, a the azimuth, $\dot{r}$ the range rate and $\dot{a}$ the azimuth rate. Equations of motion can be used to describe the target dynamics, for example, a constant velocity target would, if the time T between dwells were constant, obey

$$\begin{aligned} r(k) &= r(0) + \dot{r}kT \\ a(k) &= a(0) + \dot{a}kT. \end{aligned} \tag{2}$$

This can be expressed in known state-space form as

$$x(k+1) = F(k)x(k) + v(k) \tag{3}$$

where $F(k)$ is a known matrix, for instance in the case of a constant velocity target

$$F(k) = \begin{pmatrix} 1 & T_k & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T_k \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{4}$$

where T_k is the time between dwells k and k+1. The term $v(k)$ represents zero-mean, white Gaussian process noise as used in standard Kalman filtering. The covariance matrix $Q(k)$ of $v(k)$ is assumed to be known.

A currently used tracking method, based on the probabilistic data association (PDA) filter, as described in Y. Bar-Shalom and T.E. Fortmann, "Tracking and Data Association", Academic Press, 1988, performs tracking in the radar coordinates R, D, A, $\dot{A}$, as illustrated in Figure 2. A track is initiated by selection of a single, noisy measurement 50 with the unknown azimuth rate $\dot{A}$ being initially set to correspond with a hypothesised azimuth crossing rate, usually zero. Further measurement selection is accomplished by taking only those measurements which fall inside a validation gate 70 around the next expected position of the target measurement. This method does not require knowledge of the mapping of radar to ground coordinates during tracking. A disadvantage of this method is that it fails to use the information conveyed by multiple detections arising from multipath propagation. Also the presence of multipath propagation may cause multiple tracks 60, 62 and 64 to be generated for a single target, as shown in Figure 4, when tracking is performed in radar coordinates using conventional filters such as PDA. If the tracks 62 and 64 closely conform with the expected separations for the hypothesised modes, they can be considered to relate to the same target 52 of Figure 5, whereas a track 66 which diverges excessively can be dismissed as corresponding to another target or to clutter. Such a situation, commonly arising in conventional PDA tracking, requires a fusion or clustering operation to group multimode tracks pertaining to the same target together. This allows a track to be identified with a particular propagation mode. A further stage of coordinate registration is then required to map the tracks to ground coordinates for geographical display to the radar operators.

The preferred embodiment described herein uses explicit knowledge of the ionospheric structure including virtual heights, as provided by ionospheric sounders or by other means, to account for and take advantage of multipath propagation during track initiation and tracking. This is distinct from conventional approaches which only expect a single detection per target and are unable to benefit from the additional target-related information conveyed by multipath detections. The gain in tracking performance arising from multipath detections of a single target is important when the probability of target detection via some or all of the various propagation modes is low.

The target state is taken to be as in equation (1), where r is the ground range 8 across the surface of the earth 9, a is the true azimuth, $\dot{r}$ is the ground range rate and $\dot{a}$ is the true azimuth rate. The true azimuth a is the complement of the angle $\bar{a}$, which is the angle between the projected ground range r and the axis of the receiver array 12, as shown in Figure 5, i.e. $a = (90° - \bar{a})$. Tracking is performed in ground coordinates, although other frames of reference, for instance a preferred propagation mode, may be used to describe the target dynamics and relate these to the other measurement coordinates.

The conversion between the ground and radar coordinates can be represented as

$$\begin{pmatrix} R(k) \\ A(k) \\ D(k) \end{pmatrix} = H(r(k),\ a(k),\ \dot{r}(k);\ h_r,\ h_t) \qquad (5)$$

where, at time k, R is the measured slant range, A the measured azimuth, D the Doppler speed (slant range rate), h_r the virtual ionospheric height 53 on the receive path, and h_t the virtual ionospheric height 54 on the transmit path, as shown in Figure 5. The slant range R may be defined as one half of the total path length from the transmitter 7 via the target 52 to the receiver 4. The measured azimuth or coning angle A is the complement of the angle $\bar{A}$ between the incoming ray 57 and the axis of receiver array axis 12. The Doppler speed D is the component of the target's radial speed $\dot{r}$ along the received ray path.

The various propagation modes can be labelled according to the corresponding outbound and return propagation mode combination F_0-F_0, F_0-F_1, F_1-F_0, ..., F_2-F_2 for a target 52, as shown in Figure 3. For four possible ionospheric layers F_0, F_1, F_2, F_3 with heights h_0, h_1, h_2, h_3, these modes may be numbered from 1 to 16 respectively. Hence we may write the measurement process for the various propagation modes in terms of the target state $x(k)$ as

$$y(k) = \begin{cases} H_1(x(k)) + w_1(k) \ \ \textit{for mode } F_0 - F_0 \\ H_2(x(k)) + w_2(k) \ \ \textit{for mode } F_0 - F_1 \\ \qquad \vdots \\ H_n(x(k)) + w_n(k) \qquad \textit{for mode } n \end{cases} \qquad (6)$$

where $H_1(x(k)) = H(r(k), a(k), \dot{r}(k); h_0, h_0)$, $H_2(x(k)) = H(r(k), a(k), \dot{r}(k); h_0, h_1)$, etc., and the assumed number of possible propagation modes n may vary with time. In the above, $w_i(k)$ is a zero-mean, white Gaussian sequence with known covariance $R_i(k)$ representing the assumed measurement noise terms. The actual form of the non-linear measurement functions $H_i(\cdot)$ above is determined by the geometry of the ionospheric model as shown in Figure 5, and will depend on the virtual heights of the ionospheric layers h_r and h_t 53 and 55, and the location and separation of the receiver and transmitter arrays 7 and 12, among other factors.

Since the virtual ionospheric heights h_i in Figure 5 may only be approximately known, but are assumed to vary slowly in comparison with the target dynamics, they can be included in the state vector $x(k)$ and estimated along with the dynamical variables describing the target. In this case we have instead of equation (1)

$$x(k) = \begin{pmatrix} r(k) \\ \dot{r}(k) \\ a(k) \\ \dot{a}(k) \\ h_1(k) \\ \vdots \\ h_n(k) \end{pmatrix} \tag{7}$$

with each virtual height satisfying an equation of the form

$$h_i(k+1) = h_i(k) + v_i(k) \tag{8}$$

where $v_i(k)$ is a small process noise term.

Converting to the ground frame of reference requires the selection of an outbound and return propagation mode combination F_t and F_r with corresponding virtual heights h_t and h_r. The inverse transformation to equation (5) can be represented by

$$\begin{pmatrix} r(k) \\ a(k) \\ \dot{r}(k) \end{pmatrix} = H^{-1}(R(k), A(k), D(k); h_r, h_t) \tag{9}$$

and follows from the assumed geometry indicated in Figure 5.

Hereinafter the state prediction and associated prediction covariance are denoted by $\hat{x}(k|k-1)$ and $P(k|k-1)$ and an updated state estimate and state error covariance are denoted by $\hat{x}(k|k)$ and $P(k|k)$.

At some arbitrary time 0, tracking is initiated by selecting an initial point 50 which may correspond to a hitherto unobserved target. Since the propagation mode which gave rise to this measurement is *a priori* unknown, an initial target state estimate $\hat{x}(0|0)$ for equation (1) cannot be inferred from equation (9) unless a given propagation mode, or equivalently the ionospheric heights for the transmit and receive paths, is assumed. The preferred method is therefore to initialise n tracking filters, one for each possible initial propagation mode. Each filter assumes a particular initial propagation mode with corresponding virtual heights h_r and h_t in order to assign its initial state estimate using equation (9) based on the first measurement point 50. The estimate of the initial target azimuth rate is set to some starting value, usually zero. An initial state error covariance $P(0|0)$ is also assigned and is taken to be large enough to cover the initial uncertainty in target position and velocity. Other methods of initialisation are possible using data from more than a single radar dwell; but the previously described method is the simplest among these. Of the n filters initiated from the measurement 50, the filter based on the correct initial propagation mode assumption can be expected to perform the best and thus its state estimates would be more accurate (in the sense of having smaller errors on average) than those of the other filters initiated with it. As the processing proceeds, it becomes clear by observation of the state estimates which, if any, of the n filters initiated as above is compatible with a target whose dynamical model is assumed to be as expressed in equation (2).

The recursive processing required by each tracking filter, initialised as above, is now described. The aim of the processing is to compute, in a recursive manner, approximate conditional mean $\hat{x}(k|k)$ and covariance $P(k|k)$ estimates of the target state, based on the measurement data, including virtual ionospheric height measurements, up to time k, $Y(1)$, ..., $Y(k)$, where $Y(i)$ represents the set of measurements received in dwell i. The estimated target track is provided by plotting the range and azimuth values from $\hat{x}(k|k)$. The accuracy of the track is indicated by the size of the standard deviations which can be obtained from the state error covariance $P(k|k)$.

The dynamical target model of equation (3) is used to predict where each measurement would appear during the next dwell in the absence of measurement noise under each propagation mode. The state prediction $\hat{x}(1|0)$ at time 1 is given, in the usual manner of Kalman filtering, as described in Y. Bar-Shalom and T.E. Fortmann, "Tracking and Data Association", Academic Press, 1988, as

$$\hat{x}(1|0) = F(0)\hat{x}(0|0) \tag{10}$$

with associated covariance

$$P(1|0) = F(0)P(0|0)F'(0) + Q(0) \tag{11}$$

where F' is the transpose of the transition matrix F in equation (3). Instead of generating one gate 70, $\hat{x}(1|0)$ is used to generate n gates 72, 74 and 76 in the measurement space for each tracking filter, corresponding to the respective propagation modes F_0–F_0, F_0–F_1, ..., etc., as shown in Figure 6. The measurement predictions for the respective propagation modes are therefore

$$\begin{aligned} \hat{y}_1(1|0) &= H_1(\hat{x}(1|0)) \\ \hat{y}_2(1|0) &= H_2(\hat{x}(1|0)) \\ &\vdots \\ \hat{y}_n(1|0) &= H_n(\hat{x}(1|0)). \end{aligned} \tag{12}$$

The associated measurement prediction covariances are

$$\begin{aligned} S_1(1) &= J_1(1)P(1|0)J_1'(1) + R_1(1) \\ S_2(1) &= J_2(1)P(1|0)J_2'(1) + R_2(1) \\ &\vdots \\ S_n(1) &= J_n(1)P(1|0)J_n'(1) + R_n(1) \end{aligned} \tag{13}$$

where $J_i(1)$ is the Jacobian matrix of the non-linear measurement function $H_i(\cdot)$ in equation (6) evaluated at the state prediction $\hat{x}(1|0)$. The validation gate for each propagation mode is an ellipsoidal region in RAD space defined by

$$G_i(1) = \{y \in \mathbb{R}^3 : [y - \hat{y}_i(1|0)]' \, S_i(1)^{-1} \, [y - \hat{y}_i(1|0)] < \gamma_i\} \tag{14}$$

where γ_i defines the size of the validation gate. The probability that a target falls inside the gate i is denoted $P_G^{\,i}$, while the probability of detecting a target via the ith propagation mode is denoted $P_D^{\,i}$. This is illustrated in Figure 6 for three gates 72, 74 and 76 centred on measurement predictions 82, 84 and 86 for three propagation modes F_0–F_0, F_0–F_1, ..., etc. The gates may or may not overlap. The validation region is defined as the union of the validation gates or some region which includes their union. Points which fall inside the validation gates are accepted as possibly relating to the target 52 and are used together with the state prediction $\hat{x}(1|0)$ in order to update the state estimate $\hat{x}(0|0)$ to yield $\hat{x}(1|1)$. The corresponding state error covariance is also updated to $P(1|1)$. This process is recursive and can be represented as follows:

$$\begin{aligned} &\hat{x}(0|0) \rightarrow \hat{x}(1|0) \rightarrow \hat{x}(1|1) \rightarrow \hat{x}(2|1) \rightarrow \ldots \\ &P(0|0) \rightarrow P(1|0) \rightarrow P(1|1) \rightarrow P(2|1) \rightarrow \ldots \end{aligned} \quad (15)$$

The state estimate $\hat{x}(k|k)$ is an approximate minimum–mean–square–error estimate of the target state $x(k)$ based on all the information 48 from dwells 0 through k of the form given in Figure 2 including multiple detections of the same target due to multipath propagation. The estimate is approximate because it assumes that the probability density function of the true target state is Gaussian conditioned on all the measurement data.

To determine the updated target state $\hat{x}(k|k)$ and its covariance $P(k|k)$, the measurements falling within the gates 72, 74, 76, etc. are used in a probabilistic data association framework as described in Y. Bar–Shalom and T.E. Fortmann, "Tracking and Data Association", Academic Press, 1988, which, in addition to consideration of a measurement being from a target or due to clutter, includes association hypotheses for the possible propagation modes which may have produced the measurements. A target existence or confidence model is also incorporated in the filter as described in S.B. Colegrove, A.W. Davis and J.K. Ayliffe, "Track Initiation and Nearest Neighbours Incorporated into Probabilistic Data Association", J. Elec. and Electronic Eng., Australia, Vol. 6, No. 3, pp. 191–198, 1986, to aid in track maintenance (confirmation, deletion, etc.). The probability that the target exists at time k given data to time k is denoted $P_E(k|k)$. Target existence is modelled as a 2–state Markov Chain so that the predicted probability of target existence $P_E(k|k-1)$ satisfies

$$P_E(k|k-1) = \Delta_0 \, P_E(k-1|k-1) + \Delta_1 \{1 - P_E(k-1|k-1)\} \quad (16)$$

where the two transition probabilities Δ_0 and Δ_1 are defined by

$\Delta_0 = Pr(\text{target exists at time } k \,|\, \text{target exists at time k} - 1)$

$\Delta_1 = Pr(\text{target exists at time } k \,|\, \text{target does not exist at time k} - 1)$

An arbitrary initial value of $P_E(0|0) = 0.5$ is assumed.

As an illustration of the filtering procedure, consider gates 72 and 74 associated with propagation modes F_0–F_0 and F_0–F_1, and gate 76 associated with propagation mode F_1–F_1, with respective centres given by the measurement predictions $\hat{y}_1(k|k-1)$, $\hat{y}_2(k|k-1)$ and $\hat{y}_3(k|k-1)$, 82, 84 and 86. We will number these propagation modes as 1, 2 and 3, respectively when referring to the measurement predictions. Suppose that the gate 72 contains two measurements y_1, y_2 90 and that gate 74 contains one measurement y_3 92, while gate 76 does not contain any measurements. The 7 association hypothesis (numbered from −1 to 5) which can be applied are:

(−1) The target does not exist.

(0) The target exists but all validated measurements y_1, y_2 and y_3 are clutter.

(1) y_1 and y_3 are clutter, y_2 is a target detection via propagation mode F_0–F_0.

(2) y_2 and y_3 are clutter, y_1 is a target detection via propagation mode F_0–F_0.

(3) y_3 is a target detection via F_0–F_1 and both y_1 and y_2 are clutter.

(4) y_3 is a target detection via F_0–F_1, y_1 is a target detection via F_0–F_0 and y_2 is clutter.

(5) y_3 is a target detection via F_0–F_1, y_2 is a target detection via F_0–F_0 and y_1 is clutter.

For each of the possible associated hypothesis above, a conditional target state estimate $\hat{x}_i(k|k)$ can be formed from the predicted state estimate $\hat{x}(k|k-1)$ using the extended Kalman filter theory, as described in G.W. Pulford and R.J. Evans, "Probabilistic Data Association for Systems with Multiple Simultaneous Measurements", Automatica, Vol. 32, No. 9, pp. 1311–1316, 1996. Omitting some time indexes and writing $\bar{x} = \hat{x}(k|k-1)$ for equation (10), $\bar{P} = P(k|k-1)$ for equation (11), and $\bar{y}_i = \hat{y}_i(k|k-1)$ for equation (12), the conditional state estimates in this case are given by

$$
\begin{aligned}
\hat{x}_{-1}(k|k) &= \bar{x} \\
\hat{x}_{0}(k|k) &= \bar{x} \\
\hat{x}_{1}(k|k) &= \bar{x} + \bar{P}J_1' S_1^{-1}\{y_2 - \bar{y}_1\} \\
\hat{x}_{2}(k|k) &= \bar{x} + \bar{P}J_1' S_1^{-1}\{y_1 - \bar{y}_1\} \\
\hat{x}_{3}(k|k) &= \bar{x} + \bar{P}J_2' S_2^{-1}\{y_3 - \bar{y}_2\} \\
\hat{x}_{4}(k|k) &= \bar{x} + \bar{P}\left(J_1' \; J_2' \right) \begin{pmatrix} S_1 & J_1\bar{P}J_2' \\ J_2\bar{P}J_1' & S_2 \end{pmatrix}^{-1} \begin{pmatrix} y_1 - \bar{y}_1 \\ y_3 - \bar{y}_2 \end{pmatrix} \\
\hat{x}_{5}(k|k) &= \bar{x} + \bar{P}\left(J_1' \; J_2' \right) \begin{pmatrix} S_1 & J_1\bar{P}J_2' \\ J_2\bar{P}J_1' & S_2 \end{pmatrix}^{-1} \begin{pmatrix} y_2 - \bar{y}_1 \\ y_3 - \bar{y}_2 \end{pmatrix}
\end{aligned}
\qquad (17)
$$

where the terms J_i and S_i are as in equation (13). The corresponding conditional state error covariances $P_i(k|k)$ are given by

$$
\begin{aligned}
P_{-1}(k|k) &= c\bar{P} \\
P_{0}(k|k) &= \bar{P} \\
P_{1}(k|k) &= \bar{P} - \bar{P}J_1' S_1^{-1} J_1 \bar{P} \\
P_{2}(k|k) &= \bar{P} - \bar{P}J_1' S_1^{-1} J_1 \bar{P} \\
P_{3}(k|k) &= \bar{P} - \bar{P}J_2' S_2^{-1} J_2 \bar{P} \\
P_{4}(k|k) &= \bar{P} - \bar{P}\left(J_1' \; J_2' \right) \begin{pmatrix} S_1 & J_1\bar{P}J_2' \\ J_2\bar{P}J_1' & S_2 \end{pmatrix}^{-1} \begin{pmatrix} J_1 \\ J_2 \end{pmatrix} \bar{P} \\
P_{5}(k|k) &= \bar{P} - \bar{P}\left(J_1' \; J_2' \right) \begin{pmatrix} S_1 & J_1\bar{P}J_2' \\ J_2\bar{P}J_1' & S_2 \end{pmatrix}^{-1} \begin{pmatrix} J_1 \\ J_2 \end{pmatrix} \bar{P}
\end{aligned}
\qquad (18)
$$

where $c \geq 1$ is a scaling factor reflecting the increased uncertainty in the case that the target does not exist.

The computation of the probability of each associated hypothesis, called the association probability, can be illustrated by assuming uniformly distributed clutter measurements in the radar measurement space, and a Poisson model, as described in Y. Bar-Shalom and T.E. Fortmann, "Tracking and Data Association", Academic Press, 1988, with spatial density λ for the number of clutter points inside the validation region. Also, we let the probability of target detection P_D via any propagation mode be identical, and the gate probabilities P_G be identical. P_D and P_G are parameters that are given values which are selected to extract optimum performance from the tracking method given the operating characteristics of the system 2. The association probabilities $\beta_i(k)$, defined as the probability of the respective association hypothesis i conditioned on all measurement data up to the current time k, can be expressed as described in G.W. Pulford and R.J. Evans, "Probabilistic Data Association for Systems with Multiple Simultaneous Measurements", Automatica, Vol. 32, No. 9, pp. 1311–1316, 1996, by:

$$
\begin{aligned}
\beta_{-1}(k) &= \delta^{-1}(k)\ \{1 - P_E(k|k-1)\}\ \lambda^3/3! \\
\beta_0(k) &= \delta^{-1}(k)\ (1 - P_D\, P_G)^3\ \lambda^3\ P_E(k|k-1)/3! \\
\beta_1(k) &= \delta^{-1}(k)\ P_D(1 - P_D\, P_G)^2\ \lambda^2\ N\left\{y_2;\ \bar{y}_1,\ S_1\right\}\ P_E(k|k-1)/(3\times 2!) \\
\beta_2(k) &= \delta^{-1}(k)\ P_D(1 - P_D\, P_G)^2\ \lambda^2\ N\left\{y_1;\ \bar{y}_1,\ S_1\right\}\ P_E(k|k-1)/(3\times 2!) \\
\beta_3(k) &= \delta^{-1}(k)\ P_D(1 - P_D\, P_G)^2\ \lambda^2\ N\left\{y_3;\ \bar{y}_2,\ S_2\right\}\ P_E(k|k-1)/(3\times 2!) \\
\beta_4(k) &= \delta^{-1}(k)\ P_D^2(1 - P_D\, P_G)\ \lambda\ N\left\{y_1;\ \bar{y}_1,\ S_1\right\}\ N\left\{y_3;\ \bar{y}_2,\ S_2\right\}\ P_E(k|k-1)/(2\times 1!) \\
\beta_5(k) &= \delta^{-1}(k)\ P_D^2(1 - P_D\, P_G)\ \lambda\ N\left\{y_2;\ \bar{y}_1,\ S_1\right\}\ N\left\{y_3;\ \bar{y}_2,\ S_2\right\}\ P_E(k|k-1)/(2\times 1!)
\end{aligned}
\tag{19}
$$

where $N\{y; \bar{y}, S\}$ is a multivariate Gaussian density in y with mean $\bar{y}$ and covariance S, and $\delta(k)$ is a normalisation constant, chosen to ensure that the association probabilities sum to unity.

The updated target state estimate for the filter is obtained by summing the conditional state estimates with weightings determined by their respective association probabilities as

$$
\hat{x}(k|k) = \{\beta_{-1}(k) + \beta_0(k)\}\hat{x}(k|k-1) + \sum_{i=1}^{5} \beta_i(k)\hat{x}_i(k|k). \tag{20}
$$

The state error covariance $P(k|k)$ is obtained using standard techniques from Gaussian mixtures described in Y. Bar-Shalom and T.E. Fortmann, "Tracking and Data Association", Academic Press, 1988 as

$$
\begin{aligned}
P(k|k) = {} & \{c\beta_{-1}(k) + \beta_0(k)\}P(k|k-1) + \{\beta_{-1}(k) + \beta_0(k)\}\hat{x}(k|k-1)\hat{x}(k|k-1)' \\
& - \hat{x}(k|k)\hat{x}(k|k)' + \sum_{i=1}^{5} \beta_i(k)\{P_i(k|k) + \hat{x}_i(k|k)\hat{x}_i(k|k)'\}.
\end{aligned}
\tag{21}
$$

The updated probability of target existence $P_E(k|k)$ is obtained as

$$P_E(k|k) = 1 - \beta_{-1}(k). \tag{22}$$

Track maintenance is achieved by thresholding the target existence probability according to

$$\begin{aligned} P_E(k|k) < P_{DEL} &\rightarrow \text{delete track} \\ P_E(k|k) > P_{CON} &\rightarrow \text{confirm track} \\ P_{DEL} \le P_E(k|k) \le P_{CON} &\rightarrow \text{retain track as tentative} \end{aligned} \tag{23}$$

where P_{DEL} and P_{CON} are the track maintenance thresholds. Note $P_{DEL} < P_{CON}$. Since $P_E(\mathrm{k}|\mathrm{k})$ may vary considerably from dwell to dwell, it is better to use the average value of $P_E(\mathrm{k}|\mathrm{k})$ over the last few dwells for track confirmation in equation (23).

The above method is easily extended to arbitrary numbers of measurements falling inside the validation gates and to arbitrary numbers of propagation modes. Arbitrary clutter probability density functions and non-identical gate and detection probabilities are also easily accommodated within this framework.

A tracking filter as described above has been implemented in software using the C programming language and executed on a Digital Equipment Corporation 175 MHz Alpha workstation. The preferred implementation assumes 4 propagation modes corresponding to F_0-F_0, F_0-F_1, F_1-F_0 and F_1-F_1. The virtual heights of the F_0 and F_1 ionospheric layers are included as state variables in equation (7) and these are estimated from noisy measurements along with the range, azimuth, range rate and azimuth rate of the target.

Many modifications will be apparent to those skilled in the art without departing from the scope of the present invention as herein described with reference to the accompanying drawings.

CLAIMS:

1. A tracking method for a signal echo system, including:

generating a plurality of gates for respective propagation modes on the basis of a target state prediction for a dwell time; and

generating a target state estimate for said dwell time on the basis of target measurement points which fall within said gates.

2. A tracking method as claimed in claim 1, including:

obtaining initial target measurement points for an initial dwell time;

initiating tracking by obtaining an initial target state estimate from at least one of said initial points; and

determining said target state prediction for a dwell time subsequent to said initial time on the basis of said initial target state estimate.

3. A tracking method as claimed in claim 2, wherein a target state estimate is generated by applying association hypotheses to said measurement points in said gates and association probabilities to said hypotheses, obtaining conditional state estimates from the measurement points for each hypothesis and summing said conditional state estimates multiplied by said probabilities.

4. A tracking method as claimed in claim 3, wherein the probability of existence P_E of a target track is obtained from at least one of said association probabilities and if P_E is less than a predetermined threshold a target track maintained using said target state estimate is deleted.

5. A tracking method as claimed in claim 4, wherein said measurement points are candidate detection points in RAD space obtained from dwells.

6. A tracking method as claimed in claim 5, wherein said target state prediction is obtained from said target state estimate using linear equations of motion.

7. A tracking method as claimed in claim 6, wherein said gates are validation gates having an ellipsoidal shape in RAD space and obtained by transposing said target state prediction to RAD space for respective propagation modes to obtain measurement predictions and associated prediction covariances for respective propagation modes defining said validation gates.

8. A tracking method as claimed in claim 7, wherein said hypotheses include target does not exist, the measurement points in said gates represent clutter, and a measurement point in at least one of said gates represents a target detection.

9. A tracking method as claimed in any one of claims 2 to 8, wherein the tracking initiating step is performed for a plurality of propagation modes to initiate a plurality of tracking filters by generating a plurality of said initial target state estimates.

10. A tracking method for a signal echo system, including extending a target state vector to include additional parameters associated with a plurality of propagation modes, and accounting for measurement uncertainty associated with propagation path characteristics for said modes when updating target state estimates.

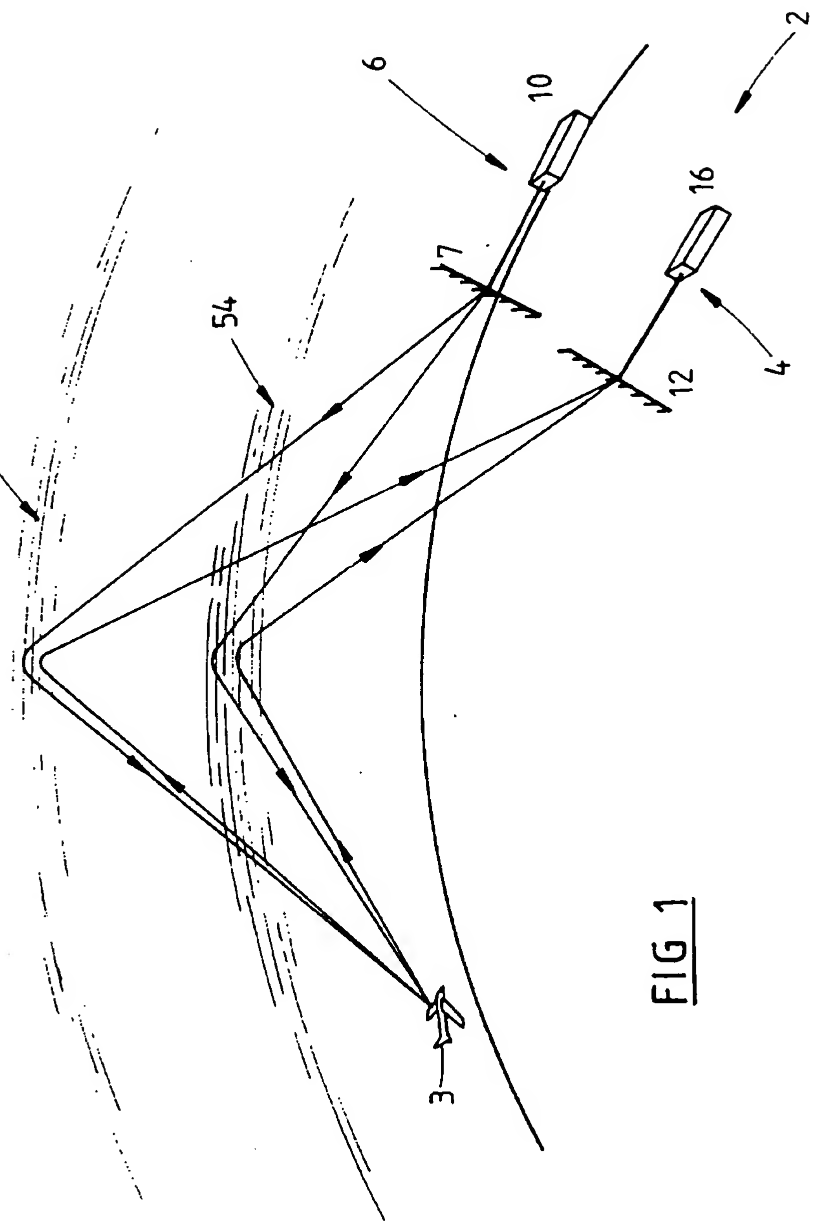

2
6
10
16
17
4
12
54
54
3

FIG 1

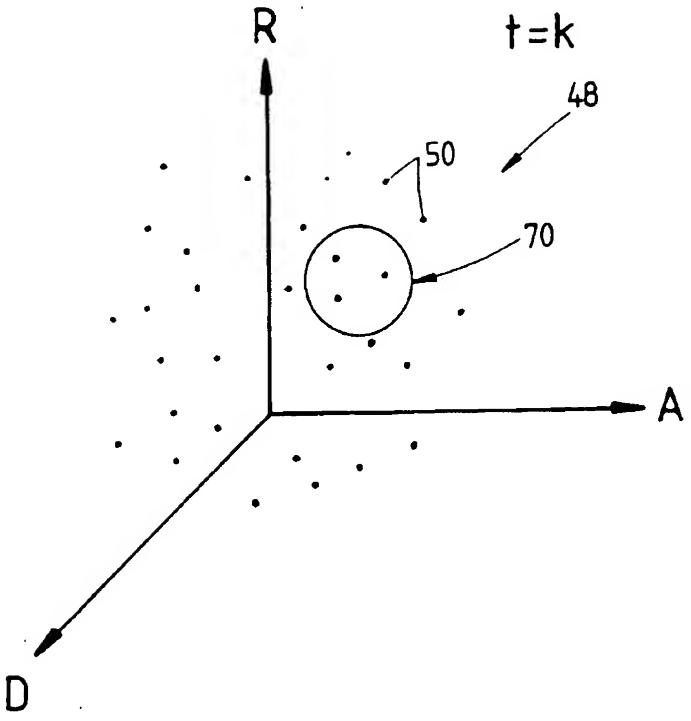
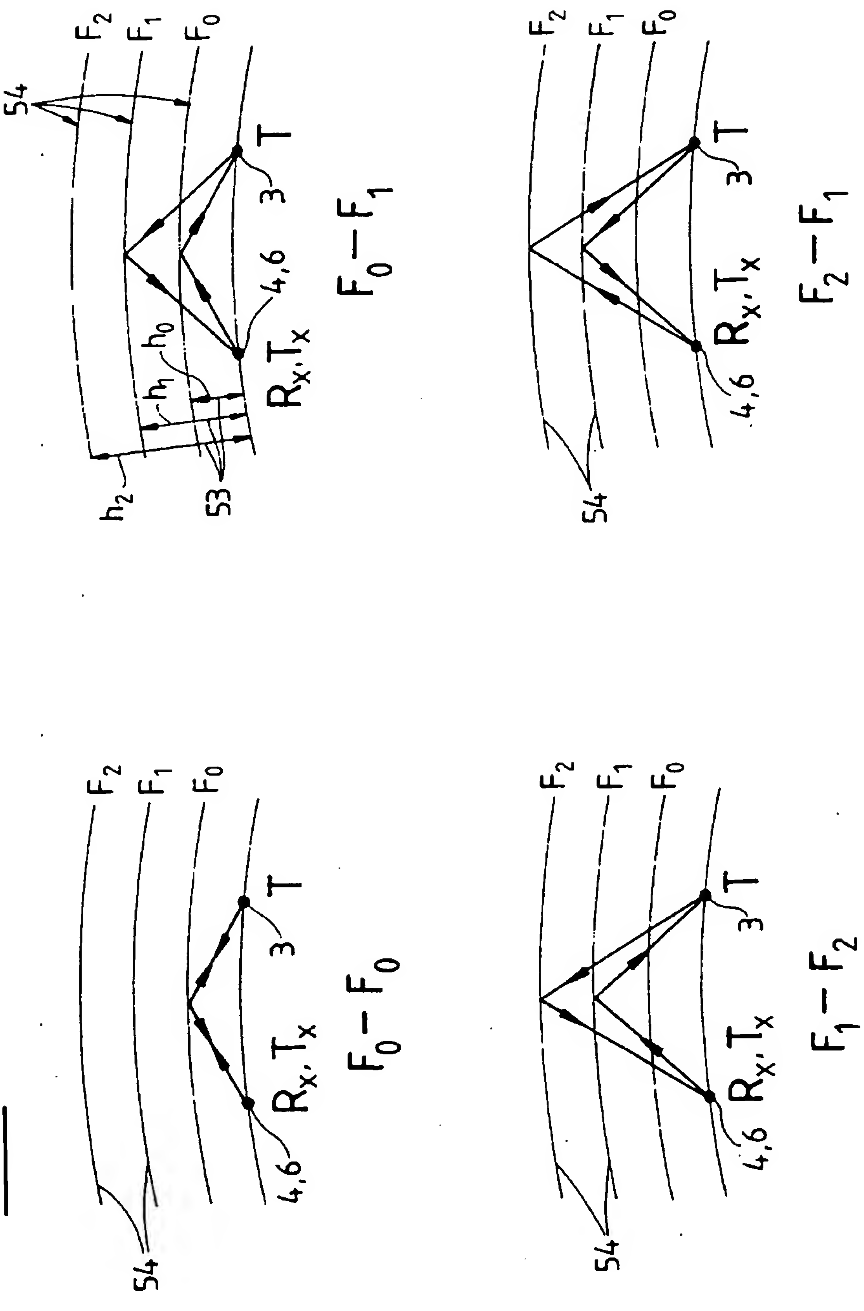

R
t=k
48
50
70
A
D

FIG 2

FIG 3


F2
F1
F0
54
T
3
4,6
R_x, T_x
$F_0 - F_0$
54
F2
F1
F0
T
3
4,6
R_x, T_x
$F_1 - F_2$
54
F2
F1
F0
T
3
4,6
R_x, T_x
h0
h1
h2
53
$F_0 - F_1$
54
F2
F1
F0
T
3
4,6
R_x, T_x
$F_2 - F_1$

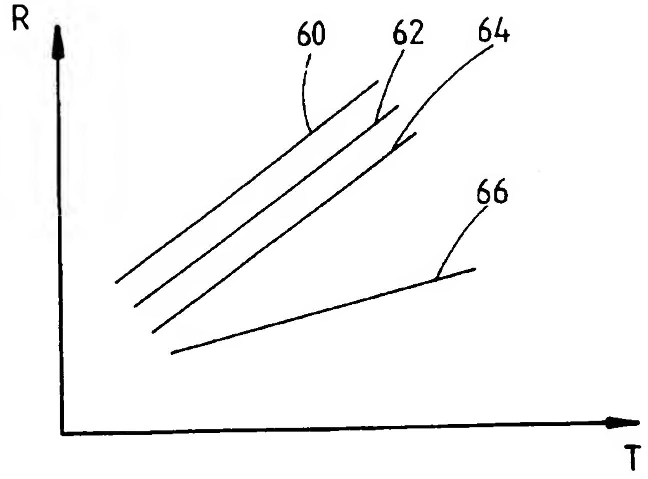


FIG 4

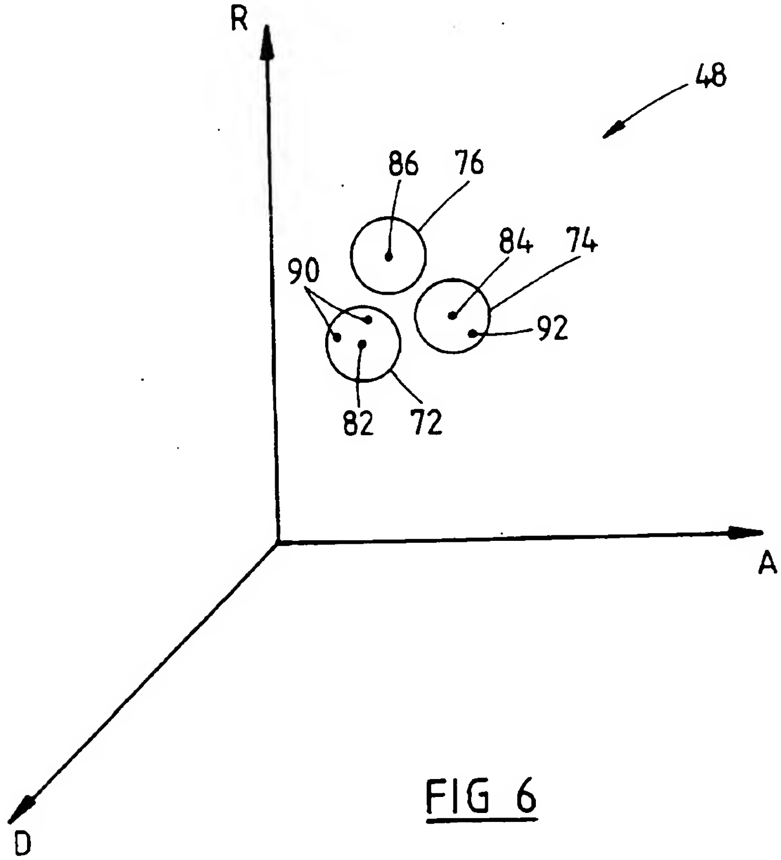

R
48
86
76
84
74
90
92
82
72
A
D

FIG 6

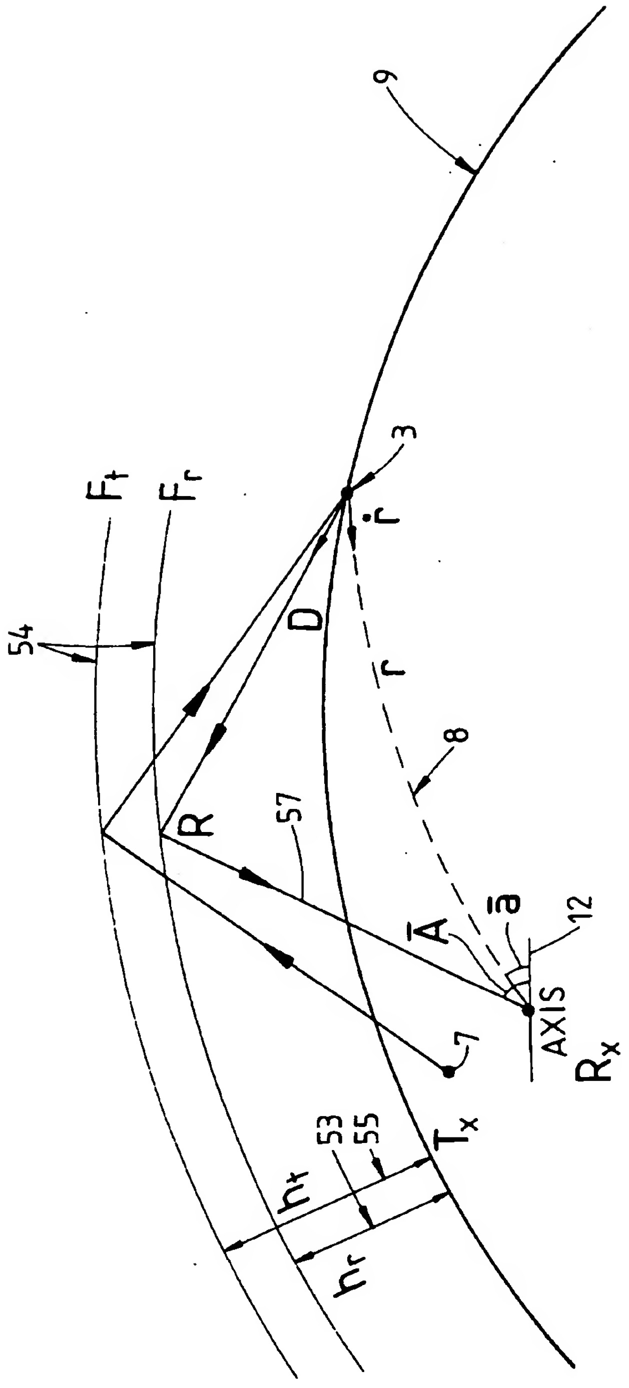

9
3
$\dot{r}$
F_t
F_r
54
D
r
8
R
57
$\bar{A}$
$\bar{a}$
12
AXIS
R_x
7
T_x
53
55
h_t
h_r

FIG 5

INTERNATIONAL SEARCH REPORT	International Application No. PCT/PCT/AU 96/00817

A. CLASSIFICATION OF SUBJECT MATTER

Int Cl^6: G01S 13/06, 13/18, 13/42, 13/72

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC: G01S 13/06, 13/18, 13/42, 13/72

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU: IPC as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DERWENT
JAPIO: GATE
COMPENDEX: RADAR TRACKING, EQUIPMENT, REFLECTION, COUNTERMEASURES

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	AU 20351/92 A (COMMONWEALTH OF AUSTRALIA et al.) 21 January 1993 page 2 line 20 - page 3 line 27 page 5 line 4 - page 6 line 26 page 8 line 29 - page 9 line 19	1, 2, 10
A	WO 94/09382 A1 (HUGHES AIRCRAFT COMPANY) 28 April 1994 Whole document	1
A	GB 2284054 A (TELEFONAKTIEBOLAGET L M ERICSSON) 24 May 1995 Claim 1	1, 10

☒ Further documents are listed in the continuation of Box C ☒ See patent family annex

*	Special categories of cited documents:
"A"	document defining the general state of the art which is not considered to be of particular relevance
"E"	earlier document but published on or after the international filing date
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O"	document referring to an oral disclosure, use, exhibition or other means
"P"	document published prior to the international filing date but later than the priority date claimed
"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&"	document member of the same patent family

Date of the actual completion of the international search 20 February 1997	Date of mailing of the international search report 24 February 1997 (24.02.97)
Name and mailing address of the ISA/AU AUSTRALIAN INDUSTRIAL PROPERTY ORGANISATION PO BOX 200 WODEN ACT 2606 AUSTRALIA Facsimile No.: (06) 285 3929	Authorized officer R.G. TOLHURST Telephone No.: (06) 283 2187

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/PCT/AU 96/00817

C (Continuation) **DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	IEEE Transactions on Aerospace and Electronic Systems, Volume 31, No.3, July 1995, G. VAN KEUK, "Multihypothesis tracking with electronically scanned radar", pages 916-927 Whole document	1-10
Y	IEEE Transactions on Aerospace and Electronic Systems, Volume 30, No.3, July 1994, B-S. Yaakov, A. Kumar, D.W. Blair, W.G. Groves, "Tracking low elevation targets in the presence of multipath propogation", pages 973-979 Whole document	1-10

INTERNATIONAL SEARCH REPORT
Information on patent family members

International Application No.
PCT/PCT/AU 96/00817

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
WO	94/09382 A1	IL	107327	US	5313212	AU	54073/94
		EP	617795				
GB	284054 A	DE	4441056	FR	2712988	NL	9401912
		SE	9303807	US	5504489		

END OF ANNEX